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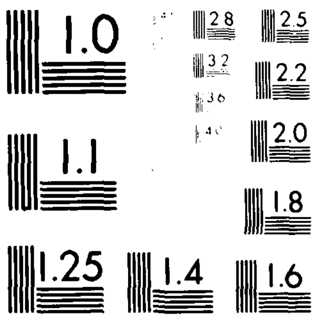

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This report summarizes research on acoustic interaction with the sea floor carried out during 1980 at Applied Research Laboratories, The University of Texas at Austin. Major topics considered are generic geoacoustic profiles for single layer sediment structures and propagation in a range variable environment. Other topics include the effects of bottom roughness (scattering) and the bottom interaction phase shift.

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I. INTRODUCTION

For a wide variety of source-receiver geometries, frequencies, sound speed profiles, and water depths, sound propagation in the oceans can be heavily influenced by the ocean subbottom. It is now recognized that this acoustic bottom interaction can have an important effect on sound propagation over ranges, frequencies, and geometries of concern to ASW applications. Applications which are affected by bottom interaction include system performance prediction, system design, interpretation of acoustical data, geoacoustic profile development, propagation modeling, and the design of experiments to gather acoustic data.

This broad range of concerns in which acoustic bottom interaction can play a significant role requires various levels of description of bottom interaction effects. Traditionally, a single quantity, bottom loss, has been used to characterize the effect of the bottom interaction. Knowledge of this quantity can be sufficient for many applications, such as ray trace calculations used to estimate propagation loss in some system performance models, which rely on a simple description of the acoustic field. However, a more detailed characterization of the sea floor is required to quantitatively understand and use more complex phenomena such as phase interference between multipaths, Doppler line broadening, multipath (or mode) conversion due to range changing bathymetry, propagation in complex shallow water environments, and questions related to array performance. Treatment of such problems, especially for cw applications, goes beyond a simple regional characterization in terms of bottom loss estimated in octave bands. Many of these problems may require fairly comprehensive descriptions of the ocean subbottom including detailed sound speed and absorption profiles, the location of reflecting interfaces, shear wave parameters, surface and basement scattering parameters, bottom slopes, and lateral changes in subbottom geoacoustic parameters.

With NAVELEX, Code 320, sponsorship through a block program administered by NORDA, Code 500, ARL:UT has been conducting a study of the influence of the ocean bottom on sound propagation characteristics. In view of the various levels of description of the ocean bottom required by the intended applications, this study has encompassed four primary research areas: (1) the influence of subbottom parameters on bottom loss, (2) the role of the bottom in range changing environments, particularly problems involving slopes, range variable subbottom structures, and bottom roughness, (3) the effect of the subbottom on the coherence of the sound field, and (4) bottom interaction effects such as those involved in array studies, cw line structure, and the interpretation of experimental acoustic data.

From the outset the primary goals of the ARL:UT bottom interaction research program have been fourfold: (1) to determine and provide guidance on the level of detail of subbottom parameters required for acoustic applications (sensitivity studies), (2) to determine which aspects of mode (or multipath) conversion caused by slope coupling, lateral variability, and roughness are predictable and exploitable, (3) to develop computational tools appropriate to the study of a wide range of complex bottom interaction problems, and (4) to interact with experimental measurement programs via exercise planning and data analysis and interpretation.

During the past contract year (FY 80) there were three lines of investigation: (1) synthesis of loss factors for thin sediments, (2) coherence, and (3) bottom interaction in range changing environments. The first two topics were new starts in FY 80 while the last was a continuation from FY 79. Research in all three areas is expected to continue into FY 81.

This report contains a summary of the progress made in each of the research areas. This work will be documented in detail through journal articles and other reports as the projects reach maturity in FY 81. Appendix A is a listing of documentation appearing in FY 80. Appendix B contains documentation for the complete project to date.

II. SYNTHESIS OF LOSS FACTORS FOR THIN SEDIMENTS

A continuing aspect of bottom interaction studies at ARL:UT is the use of bottom reflection loss as a "measure" of bottom interaction. Computational models of bottom reflection loss are used as vehicles to test the importance of one or more subbottom parameters or their uncertainties. Recent studies have explored the acoustical importance of sea floor parameters such as density, sound speed, shear speed, absorption, and their gradients.

A. Review of Previous Work

The study of the sensitivity of bottom reflection loss to subbottom parameter variations began in FY 76. Initially the work concentrated on the properties of a fluid sediment and was carried out using a computational model[1] developed at ARL:UT for this purpose. The importance of sea floor parameters such as density gradient,[2] sound speed[3] and absorption gradients,[4] and substrate rigidity[5,6] was established.

In FY 78 the direction of these studies turned toward the inclusion of shear wave propagation within the sediment. A new computational model of bottom reflection loss from a single solid sediment layer was developed[7] for use in investigating the importance of sediment shear wave excitation. Initial studies[8] using this model showed that sediment shear wave excitation is not important for thick sediment layers but could be dominant in thin layers. In thin layers the impact of sediment shear waves is greatest at low frequencies where a resonance behavior occurs. At high frequencies the resonance structure is absent but the energy lost to sediment shear waves is still substantial. The resonance structure was shown to be related to shear wave propagation within the sediment. A subsequent ray path analysis[9] of processes in thin layers established compressional wave conversion at the substrate interface as the physical mechanism generating shear waves in the sediment. This analysis resulted in a detailed understanding of the physical processes by which sediment shear waves influence bottom reflection loss. Further sensitivity studies[10] have identified important subbottom parameters affecting bottom reflection loss from thin sediment layers.

B. Major Results of FY 80 Work

The major goal of work in FY 80 was to synthesize current knowledge of bottom reflection loss from a single sediment layer into a coherent structure that would be useful for modeling applications. The need for simplification is the result of complications introduced by the effects of sediment shear wave propagation in thin sediment layers. The basic idea was to identity the major loss processes and to develop generic geoacoustic profiles and simplified computational models keyed to these processes. The distinctly different processes occurring in thick and thin layers at high and low frequencies held forth the real possibility that only a few profiles would be required.

The major loss processes thought to be important in thin sediment layers were sediment shear wave generation and propagation and also scattering from the substrate interface. For thick layers, compressional wave refraction and absorption dominate. During FY 80 profiles were developed for modeling shear wave propagation in the absence of scattering. Theoretical work to treat scattering from a rough solid-solid interface began with the aim of modeling scattering from a rough substrate. These two topics will be discussed briefly.

1. Generic Geoacoustic Profiles for Modeling Sediment Shear Wave Propagation

Three geoacoustic profiles and associated bottom reflection loss computational models were developed. The first set is a fluid sediment profile and computational model. This fluid sediment set accurately models thick sediment layers. The second is a thin sediment, low frequency set. The geoacoustic profile contains the depth dependent shear wave velocity and attenuation. The computational model includes shear wave propagation within the sediment. The final set models thin layers at high frequency. The only shear wave parameter in the geoacoustic profile is the shear wave velocity at the substrate interface. The computational model includes sediment shear waves only through the energy coupled into them at the substrate interface.

The key to developing these sets was the use of the "hidden depths" concept to quantify the thickness and frequency regimes within which different loss processes dominate. According to the hidden depths concept, originally formulated for fluid sediment structures,[11] only the subbottom structure above the compressional wave turning depth can influence bottom reflection loss and other propagation quantities. Below the turning depth there is little acoustic energy to interact with the deep structure. Hence, the structure below the turning depth is "hidden" from the acoustic field and cannot have an important acoustical effect.

Since sediment shear waves are generated at the substrate interface, the hidden depths concept allows the distinction between thick and thin layers to be quantified. Defining the hidden depth factor, HDF, as the ratio of the magnitude of the compressional wave potential in the sediment at the substrate to its value at the water interface, it was found that geoacoustic profiles for which $HDF \leq 0.01$ could be accurately modeled as a fluid. $HDF > 0.01$ required sediment shear wave parameters to accurately calculate bottom reflection loss. The transition between thick and thin occurs at $HDF = 0.01$. This transition depends upon grazing angle, through the turning depth, and frequency, through the compressional wave attenuation.

The same idea was used to quantify high and low frequency regimes in thin sediments. This time the shear wave hidden depth is used. Defining HDFS as the ratio of the shear wave potential at the substrate to its value at the water, it was found that $HDFS = 0.1$ separates the low and high frequency regimes. For HDFS$\leq$0.1, the high frequency regime, shear waves are generated at the substrate but are totally absorbed within the sediment. For HDFS>0.1, the additional resonance effects related to shear wave propagation through the sediment are also important. HDFS>0.1 requires the full set of depth dependent shear wave parameters, while HDFS$\leq$0.1 requires only the shear velocity at the substrate.

These results can be used along with relatively modest information to determine the least detailed geoacoustic profile and the most appropriate computational model needed for a given application. Given sediment thickness, type and physiographic province, it is relatively straightforward to predict fairly accurate compressional wave properties.[12] These can be used, along with frequency and grazing angle, to decide whether the sediment is thick or thin. If it is thin, very crude estimates of shear wave attenuation can be used to decide between high or low frequency. The type of geoacoustic profile and requirements for the computational model are then chosen.

The ability to determine the level of detail required to adequately model sediment shear wave effects is a matter of practical interest. If the sediment in an area is thick for the intended applications, it is not necessary to carry out experiments designed to measure shear wave parameters. If the application is high frequency it is not necessary to develop modeling techniques to handle the short wavelength, heavily attenuated sediment shear waves; only their excitation needs to be modeled. Knowing these requirements before the fact can save substantial computational effort and complexity.

Final sensitivity studies for the thin, low frequency geoacoustic profile have been completed and detailed documentation will be available in FY 81.

2. Modeling Scattering from the Substrate

Substantial progress has been made in developing the theoretical framework to model scattering from the substrate. The current work was initiated when it became apparent that the solid properties of the sediment needed to be included. An extension of the mean boundary condition approach as applied to fluid-fluid interfaces[13] was considered but was not implemented because the theoretical limitations on the height and correlation length of the roughness would not allow frequencies and geometries of interest to be investigated. Initial studies showed that this approach might be reformulated so that the restrictions on the height could be substantially relaxed. The present effort is based on an expansion in which all corrections due to two-point correlations are included but higher order correlations (three-point, etc.) are neglected. This approach makes use of the root mean square height of the roughness and the correlation length, the quantities most likely to be measured, as parameters. It is expected that this work will be completed and implemented in FY 81.

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III. COHERENCE EFFECTS

During FY 80 work was begun on two aspects of bottom interaction effects on the coherence of the sound field. The first of these is an effort to determine the level of detail required in the geoacoustic profile of the subbottom to adequately predict the phase of bottom reflected energy. The second is a study of bottom interaction effects on multipath degradation of coherence.

A. Sensitivity Studies of the Bottom Reflection Phase Shift

The idea behind this work is to use the phase of the plane wave reflection coefficient as a measure of the effect of the ocean bottom on the phase content of the acoustic field. Numerical models of bottom reflection loss are then used to find the sensitivity of the bottom reflection phase to subbottom parameters and their uncertainties. This approach is analagous to that used to investigate the sensitivity of bottom reflection loss to subbottom parameters. The basic question to be answered is whether a more detailed subbottom description is required to adequately predict the bottom reflection phase than is necessary to predict the magnitude of the reflection coefficient. Sensitivity studies to answer this question are in progress. Particular attention is being paid to studying the generic geoacoustic profiles developed to model bottom reflection loss.

Additional work is in progress to determine the role of "beam displacement" and "beam delay" in ray trace modeling of signals from impulsive sources. The existence of beam displacement has been known for some time but has only recently been applied to underwater acoustics problems.[2-4] Beam displacement is an additional phase shift that is equivalent to a displacement of the position at which the ray leaves the ocean bottom from the point at which it enters the bottom. This concept is relevant to the use of plane wave reflection coefficients in ray trace propagation models. It is a measure of how fast the bottom reflection phase changes with grazing angle. Related to the beam displacement is the beam delay which is an additional phase shift related to the rate at which the bottom reflection phase changes with frequency. Sensitivity studies are in progress to investigate the level of detail required of the geoacoustic profile to accurately predict these quantities.

B. Bottom Interaction Effects on Multipath Degradation of Coherence

In general, the phase information of the acoustic field is not used directly, but in a form resulting from the signal processing found in multisensor systems. System dependent quantities are then an inherent part of the problem.

Beamforming is a typical application. The beamforming process is essentially equivalent to spectrum analyzing the individual sensor signals, phase shifting the frequency components, summing over sensors, and computing the average magnitude squared of the sum. Mathematically, this results in the phase information of the acoustic signal appearing in a statistically averaged quantity called coherence.

Work is now in progress to study the effect of bottom interaction on the coherence of the sound field from a slowly moving cw source. Doppler effects are not included at this time. The constant velocity source motion results in signal fluctuations at a stationary receiver as the multipath structure moves past the sensor. The fluctuations during an integration time result in a decreased coherence relative to that of a stationary source. This multipath (multimode) degradation will depend upon both range and depth through the structure of the acoustic field. This degradation is deterministic in origin. It is not related to fluctuations in the medium or interaction with rough surfaces but occurs solely because of the averaging which is an essential part of the beamforming process in the presence of noise.

The effect of bottom interaction cn the multipath degradation of coherence is being studied by simulating the beamforming process. The ARL:UT normal mode model NEMESIS is being used to generate the mode description of the acoustic field. The modes are propagated in range from the source to the sensor location where the coherence function is computed. The time average is accomplished by a range average over an interval corresponding to the source motion during an integration time.

Software development has been completed and studies using the same geometry with sediment attenuation as a parameter are currently in progress. This allows a comparison of strong and weak bottom interaction for the same geometry. The coherence of receivers in the sound channel and those near the bottom are being investigated and compared.

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IV. BOTTOM INTERACTION EFFECTS IN A RANGE CHANGING ENVIRONMENT

The work encompassing acoustic propagation in a range variable environment is summarized in this section. The effect of both sloping bottom and lateral subbottom variability is discussed.

The work on sloping bottoms has the goal of determining which factors significantly influence acoustic propagation in such areas. One such factor is the particular geometry, e.g., continental slope, sea mount, etc. A second factor influencing propagation is the bottom composition. After determining the relative importance of the geometry and the geoacoustic profile of the bottom, a second goal is to ascertain the level of detail in geometry or bottom geoacoustics necessary to characterize propagation.

In the study of acoustic propagation in the presence of lateral variability the relevant issues are the extent to which naturally occurring inhomogeneity is a significant factor and the method to be employed for including such effects in the propagation model. Propagation through regions with geoacoustic profile variations is of particular interest for large source-receiver separations. A description of the propagation in such a case would be considerably simplified if a range averaged geoacoustic profile was adequate.

A. Review of Previous Work

1. Sloping Bottom

Two aspects of propagation over a sloping bottom were examined during FY 79. First, multipath conversion effects were shown to be included in the adiabatic approximation.[1] Second, the theory of coupled modes was extended beyond the adiabatic approximation.[2] As a result, the boundary condition on the derivative of the acoustic field normal to the slope was shown to be consistently approximated within the adiabatic theory by the depth derivative.

2. Lateral Variability

At the beginning of FY 80 the numerical model ADIAB was available to calculate transmission loss for a range variable waveguide. The model is based on the adiabatic approximation. The overall organization and implementation is described elsewhere.[3]

B. Results of FY 80 Research

1. Sloping Bottom

The numerical model ADIAB was employed in a study of the sensitivity of upslope and downslope propagation to subbottom attenuation. Solutions of the equations describing the variation of the coupled normal modes with range were studied in detail. Methods of introducing mode-mode coupling into ADIAB were also considered. These topics are discussed in Reference 3. A brief summary of the results of the sensitivity study is given here.

The most notable conclusion from the sensitivity study was the finding that the acoustic field, both in shallow water after upslope propagation and in deep water after downslope propagation, was particularly sensitive to the shallow water bottom attenuation. This sensitivity to the shallow water bottom attenuation becomes more pronounced with increasing source-receiver separations for both upslope and downslope propagation. For upslope propagation the importance of bottom interaction mechanisms increases from deep to shallow water and some sensitivity to slope angle exists, especially for deep or shallow source depths. On the other hand, during downslope propagation, bottom interaction mechanisms decrease in importance from shallow to deep water and no particular sensitivity to slope angle is evident. Finally, an enhancement of the acoustic field, especially for sources in the deep sound channel, is possible in upslope propagation.

2. Lateral Variability

Work began, using the ADIAB model, on a sensitivity study and range averaged description of range varying sediment attenuation in shallow water environments. Several conclusions can be made. One is that range varying gradients in the depth dependence of the attenuation are relatively unimportant for horizontally stratified sediments. Second, if a region of greatly increased attenuation (absorbing patch) is present between source and receiver in a horizontally stratified environment, the received intensity is independent of the location of the patch (midway, closer to source, closer to receiver). Put another way, the received intensity will depend upon the range of the source and upon the patch attenuation but not upon the placement of the patch between the source and receiver.

C. Future Directions

The separation of problem areas into questions concerning the effect of slopes and the effect of lateral variations leaves the relative importance of slope geometry and lateral variations still to be determined. The study of energy partitioning in such a problem is likely to be quite relevant. Finally, in the main line of research areas, the utility of range averaged models and their alternatives needs further investigation as well.

From a broader perspective, the problem of range variability in three dimensions remains virtually unexplored. Although the general problem in three dimensions does not appear to be soluble in a practical way, more specific problems, such as diffraction effects in the presence of sea mounts, should be more tractable.

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The authors gratefully acknowledge the work of Susan Payne, Terry Foreman, and Ruth Gonzalez in developing the extensive and sophisticated computer software required for carrying out the computations central to this research.

This research receives continuing stimulation from concurrent research at ARL:UT under the direction of Drs. Steve Mitchell, Claude Horton, and Clark Penrod. Much of the work on propagation in range variable environments was made possible by initial work done by Dr. S. R. Rutherford.

APPENDIX A
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APPENDIX B
NAVELEX/NORDA
BOTTOM INTERACTION PROGRAM
DOCUMENTATION

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